DEVELOPMENT OF A RIVER SEDIMENT TRANSPORT MONITORING SYSTEM FOR LARGE RESERVOIRS

T. A. Cochrane, L. D. Norton, C. Castro−Filho, J. H. Caviglione

ABSTRACT. *Determining the amount of sediment being transported by rivers is fundamental to determine the environmental impact on reservoirs, as well as to estimate their life span. This monitoring is particularly important for large hydroelectric dams such as the Itaipu hydroelectric facility on the Paraná River, which provides over 24% of the electricity needs for Brazil. A system was developed to continuously monitor sediment transport in the main rivers of the watershed acting on this reservoir using specifically developed turbidity sensors, commercial water level meters, manual sediment sampling, and laboratory analyses. The turbidity sensor was designed using a single optical sensor chip and light source LED that works with a single 9V battery, which can last over 4 months of continuous hourly monitoring. An economical commercial data logger was used to trigger readings and store the sensor response. This data, together with laboratory analyses of sediment samples were used to constantly calibrate sensor readings and determine sediment concentrations in the rivers. Total suspended loads were calculated using river water flow rates as determined by the water level meters and velocity profile measurements. Furthermore, two types of structures were developed to house the sensors in the rivers: 1) buoys and 2) structures fixed to the pillars of bridges. Although both structures protected the sensors well during extreme flow conditions, the buoys required less maintenance because of their constant movement, which limited fouling of optical sensors. Comparisons of laboratory analyses showed good correlation between turbidity sensor readings and manual sediment sampling. This system enabled an economical and continuous monitoring of suspended sediment load for a variety of river conditions. The monitoring results were used to determine total sediment contribution to reservoirs.*

Keywords. *Turbidity sensors, River monitoring, Sediment transport, Reservoirs, Sedimentation.*

Large investments in dam construction can sometimes be at risk because of unforeseen changes in land use, which increase silting of the reservoir. Increased agricultural production can lead to an increase in land degradation and sediment production within the watershed, which eventually accumulates in reservoirs. This was a cause of particular concern for the Itaipu hydroelectric dam and reservoir in the Paraná river basin in southern Brazil, which is the worlds largest electricity producer with a current output of 12,600 MW enabling it to provide 24% of Brazil's electricity needs and 95% of Paraguay's (Itaipu Binacional, 2004). This potential increase in sediment production because of an increase in agriculture acreage in the drainage basin could pose a long−term threat to the reservoir and the future production of hydroelectric energy. This concern has increased recently in Brazil because of recent energy shortages. An increase in sedimentation of reservoirs can also potentially promote eutrophication and thus have a severe effect on aquatic ecosystems. Additionally, a substantial increase in sedimentation over the long−term can disrupt navigation in reservoirs and rivers. In order to determine the reservoir sedimentation rate and establish conservation strategies to reduce the production of sediment, a methodology has been established to continually monitor the sediment load in rivers contributing to the reservoir.

Determination of sediment concentration in rivers has been approached in a variety of ways. The most common method to determine the amount of sediment flowing down rivers is through periodic manual sampling of the waters and relating these measurements with stage height or total flow rate to obtain equations for total sediment load. Recently, this method has been improved using automatic samplers that take daily samples and store samples for later analysis. The problem with daily or weekly sampling is that peak sediments concentrations are often missed. Peak sediment concentrations are usually responsible for carrying the vast majority of the total sediment load. Sediment concentrations and stage heights or flow rates may also peak at different times, especially in very large basins.

Since the early 1990s, turbidity sensors have become more available and have been used to measure suspended sediment concentration (SSC) in rivers and streams with different levels of success. Gippel (1995) observed that for estimating monthly or annual sediment loads, the relation between SSC and turbidity will vary over time with changes in sediment sources, organic loading, or sensor calibration. Additionally, Schoellhamer (2001) suggests that the use of optical sensors should be evaluated on a site−specific basis and consider the objective of the measurement, potential particle size effects, and potential fouling. Monitoring sediment with turbidity

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sensors has usually required a statistically significant relationship between the turbidity and the suspended sediment concentration (Sun et al., 2001).

A variety of commercially available turbidity sensors are now available that have been adapted from the food processing industry; however, prices can be economically forbidding and sensors can be too delicate for field use. Lewis and Eads (1998) mentioned that sensor−housing design is an area that still needs more research and development. It was suggested that the ideal probe housing should shed debris and protect the probe from traumatic impacts, while allowing the stream suspension to flow through. The success and limitations of different structures used to house turbidity sensors for monitoring streams and small rivers are discussed by Lewis and Eads (2001). Additionally, most commercial turbidity sensors require a fixed source of energy in a gauging station. For example, in a gauging station in Palomo, Costa Rica, water is pumped from a fixed point in the stream to a fixed turbidity sensor (Jansson, 1996). Few, if any, commercial sensors are available for extended use in turbulent river conditions.

In this study, we provide a way to continuously monitor sediment load in rivers through the development of new field adapted turbidity sensors and structures to house them, as well as manual sediment sampling routines and water level measurements required to constantly calibrate the sensors and verify sediment loads. Manual sampling of sediment permits a continuous calibration of the turbidity sensor, which together with regular maintenance helps overcome issues such as accumulation of algae and sediment on the lenses of the turbidity sensors that may cause monitoring errors.

The monitoring of sediment and the identification of high−risk areas could lead to better policies for the implementation of conservation practices within the watershed, which in turn would benefit both the Itaipu hydroelectric dam and agriculture in the watershed.

MATERIALS AND METHODS

The first challenge in developing the system to measure sediment load in the rivers was the design of the turbidity sensor. The turbidity sensor was developed complying with a series of required characteristics for monitoring the rivers in southern Brazil. The sensors had to be designed so that they could withstand being left in the field for extended periods of time. The sensor probe had to be rugged enough to withstand flash floods and immersion in river water with up to 15 m of head. The housing of the sensor also had to be constructed to minimize influence by solar daylight. The sensor electronics had to be designed to run on a small 9V acid−lead or alkaline battery without external power or a solar panel for an extended period of time (4−6 months) while making a reading at least every hour during this time. The sensitivity of the sensors had to be designed to have a wide range for measuring turbidity to be able to measure suspended sediment in the large and small rivers of the region. Additionally, the sensor had to be more economical than commercially available turbidity sensors and be easy to maintain or replace in the field.

DESIGN OF THE TURBIDITY SENSOR

A turbidity sensor was designed and developed to measure SSC using readily available electronic components and a simple schematic as shown in figure 1. The complete sensor setup consisted of a data logger, a control box, and a probe connected to the control box by a three−wire cable. Even though more complex turbidity sensors found commercially measure both reflectance and transmissivity of light through the medium (river water), for our case we opted for a simple design that measured only transmissivity of light. This reduced the costs and kept maintenance of the sensors to a minimum. Laboratory tests conducted while designing the sensor did not show a significant gain in precision by incorporating reflectance measurements in the sensor for the red clay suspended sediments typical of rivers in the lower Paraná River basin.

A rugged and economical commercial data logger was chosen that was suitable for use with the required characteristics of the turbidity sensor. The chosen logger was the HOBO, Outdoor/Industrial 4 Channel External, manufactured by Onset Computer Corporation (Bourne, Mass.). This particular logger has four analog channels that read voltages in the range of 0 to 2.5V or current 4 to 20 mA. The logger can be easily programmed with a computer to log data at any time interval, from seconds to minutes to hours to days. For our specific purposes, the logger was programmed to make readings at every hour interval, using two channels (channels 3 and 4) as shown in figure 1. Channel 3 (V_{H3}) takes a voltage reading of the 9V battery to check its status and channel 4 (V_{H4}) takes a reading of the actual turbidity sensor output voltage. At every hour, the logger sends an initial “wake up” current (V_T) that is maintained until after it makes the reading. The “wake up” or trigger is activated by channel 3 for 4.5 milliseconds (ms) before any readings are made. The channel 3 is then read for 2 ms and then channel 4 is read after a time delay of 14.5 ms. The trigger is then shut off 11 ms after the last channel is read. The readings are then stored with the actual time and date. The accuracy of the logger is ±10 mV or ±1% of the reading. It can operate in −20°C to 70°C of temperature and can store 32,520 time−sampled measurements in nonvolatile memory.

The control box houses the battery and circuitry that provide power to the electronics in the probe. The circuitry in the control box is composed of a few resistors to regulate the voltages and an optical switch (TIL111). The optical switch is triggered by a low voltage from channel 3 (V_T) of the data logger. A green LED is used to visually determine that the sensor is working as the schematic in figure 1 shows. Since the trigger time is very short (4.5 ms), the circuit is very dependent of the TIL111 and its properties. The reaction time for the TIL111 chip is dependent on the manufacturer, so it is recommended that chips from only one manufacturer be used and that resistors be adjusted accordingly. The location of the resistors are shown in figure 1; however, actual values are not shown since they need to be determined according to requirements and can also be used to calibrate the circuitry.

Once the TIL 111 chip is triggered by the low voltage from the data logger, it basically turns on the power (9V battery) for the circuitry in the probe. The circuit in the probe is composed of a light emitting diode (LED) and a monolithic photodiode with an on−chip transimpedance amplifier (OPT101). The OPT101 output voltage increases linearly with light intensity. Technical specifications for this chip are

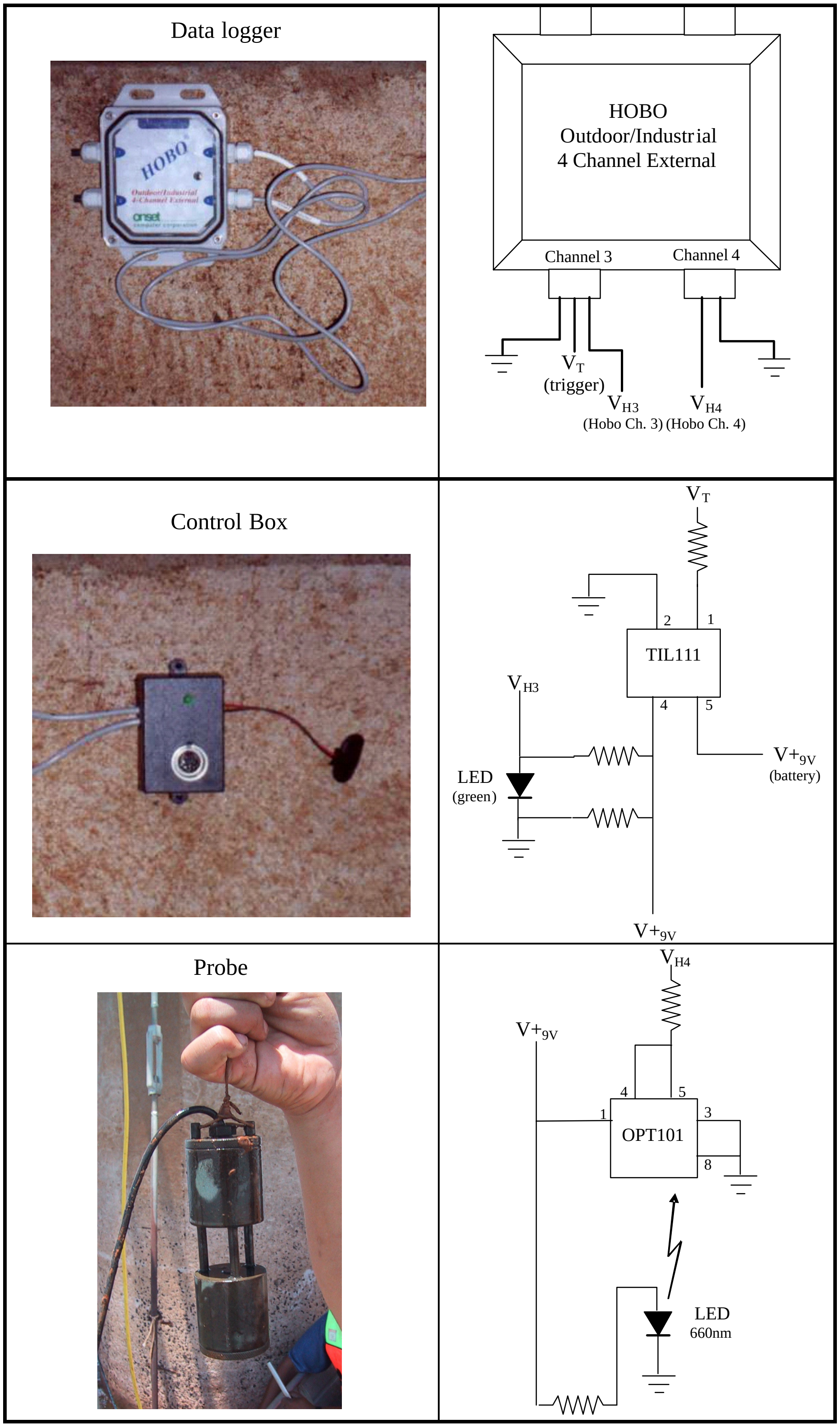

Figure 1. Components of the turbidity sensor.

ideally given for a 650−nm light wave (Burr−Brown, 1998). The LED was chosen to fulfill the requirements of the OPT101 as well as to exceed the possible range in sediment concentration in the rivers. The maximum sediment concentrations from historical series of manual samplings were under 500 mg/L and therefore LED's were tested to exceed these requirements and be able to measure turbidity in the range of 0 to 2000 nephelometric turbidity units (NTU's). After testing a variety of LED's, the chosen LED had a 5000−mcd light output and a consumption of 1.82V at 20 mA while emitting a 660−nm light wavelength (red light).

Experimental testing during development showed that the spacing between the LED and the OPT101 was also very important. The ideal distance in the medium, in our case river water, between the OPT101 and the LED was 36 mm, which was incorporated into the design of the probe as shown in figure 2. An 18−mm long and 4−mm wide channel was also designed into the probe to reduce the presence of ambient light. The probe was also designed to maximize the flow of water between the LED and optical sensor and minimize accumulation of debris or sediment on the lenses. Variance of temperature in the probe that could have an effect on the OPT101 or LED is minimal since it remains underwater where the variation in temperature is minimal.

The probe was made using a brass alloy material with 65.5% to 68.5% copper and the remainder being zinc. Some probes which were made with black nylon worked just as well. The probes were made by machining a round bar of the material into two parts that are connected by three rods. One of the rods was hollow which allowed wiring to go between the parts. Inside the probe, a specially machined socket was used to mount the OPT 101 on the top side of the probe and another socket was used to mount the LED bottom part to minimize the effect of ambient light (fig. 2). Once the electronics were in place the sensor was filled with resin to prevent moisture from damaging the circuits. An acrylic lens and o−rings were used to seal the top and bottom casing. A 0.5−mm protrusion of the acrylic lens diminished accumulation of sediment on the center of the lens. Water infiltration or leakage tests were conducted on the probes at over 20 atms and the probes were verified to be waterproof.

For the monitoring locations that required further waterproofing, the control box, 9V battery, and HOBO data logger were placed in an o−ring sealed acrylic container as shown in figure 3. The acrylic box was connected to the probe by a cable inside a 10−mm heavy duty rubber hose that provides adequate protection and waterproofing.

Water Level Meter

The water level meter measured the change in pressure head of the water from a fixed point inside the river and thus measured the water level of the river. Electronic water level meters, which were readily available commercially at relatively low costs, were chosen to match the specific range of possible change in the stage height of each of the rivers as determined by historic measurements since the building of the Itaipu dam. In our case Global Water WL14 water level meters were chosen that feature a self−contained data logger (Global Water, 2000). The logger was programmed to take hourly readings, which provides the capacity to store up to 9 months of stage data. Data obtained from the sensor was used with a calibrated flow velocity curve at the respective section of the river to calculate the river flow rate. The flow velocity curve was determined by obtaining various profiles of the river velocity using an ADCP (Accoustic Doppler Current Profiler) at varying stages. This flow velocity curve permits a computation of water discharge as a function of

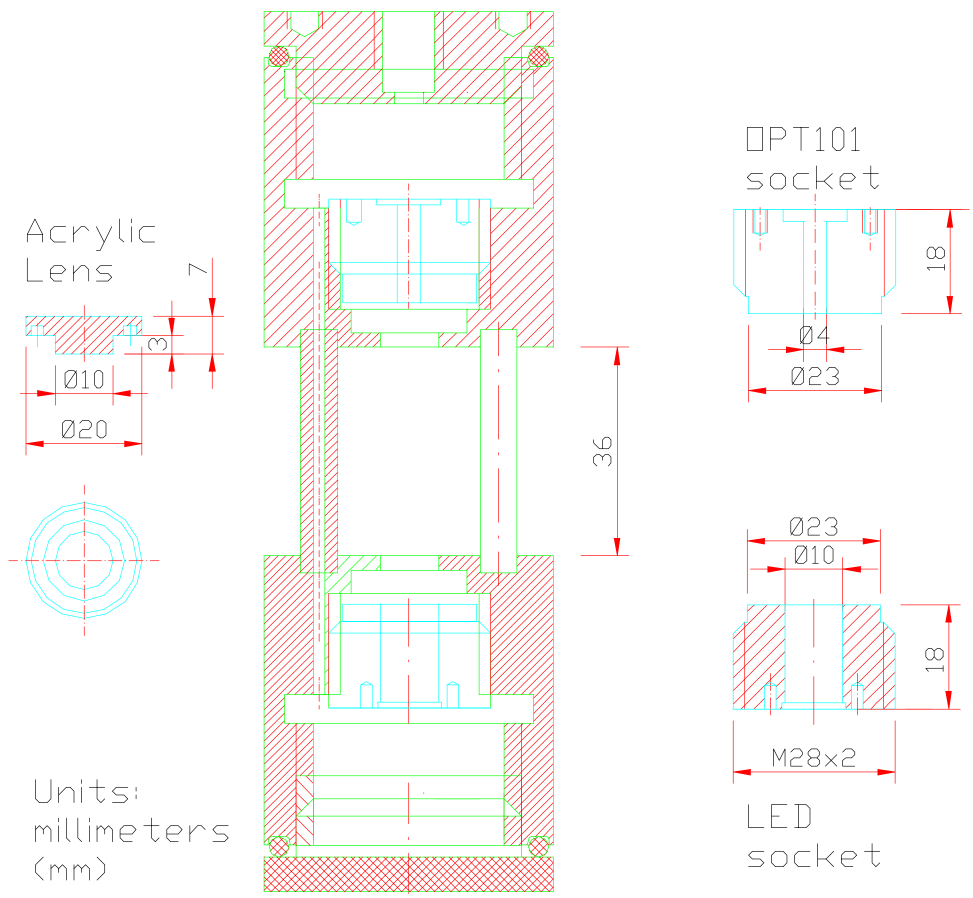

Figure 2. Probe design showing OPT101 and LED sockets and acrylic lens.

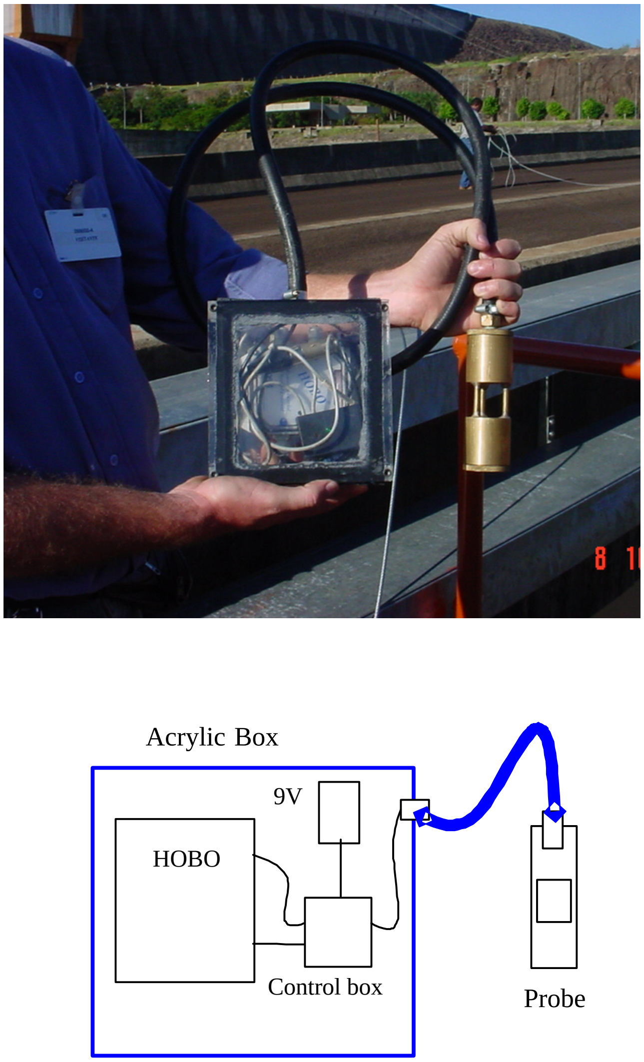

Figure 3. Waterproofing the control box, battery, and data logger.

stage height. Total sediment transport down the river is then computed as a product of discharge and sediment concentration.

Monitoring Station Structures and Buoys

Two types of monitoring stations were used to house the equipment. The first one (shown in fig. 4) was a permanent structure mounted on the pillars of bridges. These structures were pre−built and installed on the pillars using braces without damaging the pillars. A 12−mm galvanized pipe was used to protect the water level and turbidity sensor probes. The bottom of the tube had adequate 10−mm perforations to permit water to flow freely through the tube. This station included a metallic box which housed both a water level meter and a turbidity sensor as shown in the figure 4 (a, b). Data was easily downloaded to a portable PC or handheld Palm digital agenda using extended cables or by access with a ladder.

The other type of monitoring station that was commonly used in situations where bridges were not present, or when construction of a permanent station was not possible, was a buoy (fig. 5). The buoys were built to house only a turbidity sensor (fig. 5a and b) because they floated on the surface of the water and varied with water level. Two types of buoys were developed and were specifically designed to withstand harsh river conditions. One was designed to slide up and down a cable attached from the top of a bridge to a heavy anchor in the bottom of the river (fig. 5c and d). In order to prevent the anchor from being dragged by the river flow, a chain was placed around the pillar and attached to the anchor. The chain sank to the bottom of the river and kept the anchor at a constant distance from the pillar. The second type actually consisted of a system of two buoys. One buoy was attached to an anchor by a strong cable to the bottom of the river and the other was attached to the first main buoy as shown in figure 5a and b. Both buoys that hold the sensors were made with a 100−mm galvanized steel pipe with two or three 800−mm diameter lifesavers attached to the pipe through a welded structure (fig. 5). A metallic box was welded on top of the galvanized pipe, which held the acrylic box with the HOBO and electronics. The probe sat at the bottom end of the galvanized pipe submerged under the water. The submerged end of the galvanized pipe was drilled with 10−mm holes to permit an easy flow of water through it. The probe could easily be taken out from the top of the metallic box. Data obtained from the sensor in either of the buoys could easily be downloaded to a personal portable or palm sized computer by accessing the buoy with a boat. In places where there was no access via boats to the river a third modification could be done to pull the buoy to the top of the bridge to obtain access to it; however this system required a platform on the bridge. This system worked with a counter weight that has two purposes (1) to keep the cable tightly attached to the buoy regardless of the change in the river

Figure 4. Monitoring station structures attached to bridge pillars in the river.

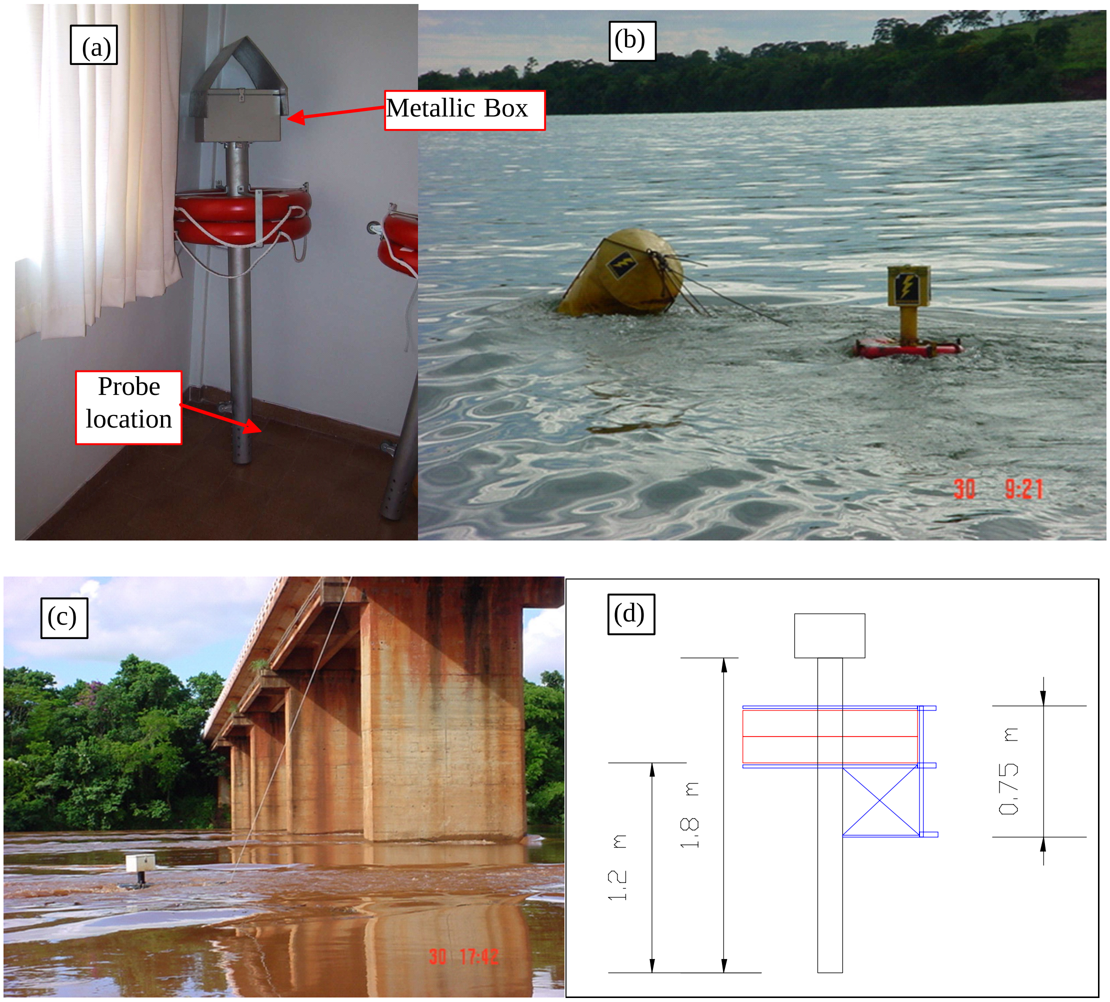

Figure 5. Buoys used to house turbidity sensors in rivers.

water level and (2) to ease the lifting of the buoy to the top of the bridge for maintenance and data downloads.

Manual Sampling and Maintenance

In Brazil, as in most developing countries, it was more economical and practical to contract people that live close to the sampling point to take water samples, look after the equipment, and report by phone any odd occurrence. This setup was possible because in most locations there was already someone contracted to take care of stage recorders originally in place. In the new sampling locations, the people participated in the whole process starting with installation and continuing with the maintenance. In some rivers in the Paraná River basin, large events can transport large quantities of debris (tree branches, logs, and other vegetation), which then accumulate around pillars and disturb the buoys. In these cases, caretakers immediately removed any debris that was interfering with the functioning of the buoy. Sampling of water was done three times a week using two 1−L grab samples in plastic bottles at a depth of about 0.5 m and at the same location of the turbidity sensor. At these turbulent regions of the river flow, there was sufficient vertical mixing of sediment to obtain a representative sample from the river. The data and time of sampling was logged for every collection. These samples were then analyzed gravimetrically in two different laboratories and the results were compared to verify accuracy. A large database was developed using MS Access to organize and analyze the data.

Laboratory Analyses

Laboratory analyses of the collected water samples were carried out using an adaptation of standard analysis methodologies (Carvalho et al., 2000a, b). As is common practice, 0.45−micro meter celluloid filters were used to collect sediment from river water samples with little observable sediment. Samples with large sediment concentrations had to be analyzed by flocculation of sediments and decanting in a beaker. These modified procedures thus made use of a commercial laboratory turbidity meter to check NTU (nephelometric turbidity units) and thereby differentiated samples for filtering and samples for decanting in a beaker. Efficiency was a concern because of the number of samples to be processed every month, and the laboratory turbidity meter was ideal to help screen samples quickly. After experimentation with water samples from the different rivers using results of the time required to filter samples, clogging of filters, and accuracy of measurements, a cutoff point at 15 NTU was implemented for use of filters versus beakers. Analyses of the samples with less than 10 NTU were unreliable using the beaker method, and those samples larger than 20 NTU would clog the filter. A system of two laboratories was also set up to check analytical results.

Crosschecks between laboratories were carried out to check the accuracy of laboratory analyses by collecting two samples and sending one to each lab.

PROCEDURES FOR CALCULATING TOTAL SEDIMENT LOADS.

Components of monitoring (turbidity sensor outputs, flow rates, manual water sample collections, and laboratory analyses) provided data required to calculate suspended sediment loads in the rivers being monitored. The procedure started with the filtering of data to exclude outliers and errors from laboratory analyses or sensor voltage outputs. The cross checks between laboratories analysis results helped in this process. Sudden hourly peaks in turbidity sensor readings can also be attributed to some type of irregularity, which must be corrected. Turbidity sensor voltage output was then calibrated with the laboratory analyses to obtain SSC. An equation was fitted to the data to obtain the best relationship between sensor output voltage and SSC. Results were then verified with flow rate of the river. Calculation of total sediment transport in the river was then obtained by multiplication of the river water flow by sediment concentration and performing appropriate unit conversions. Customary units for sediment concentrations are mg/L, and river water flow is in m^3/s.

RESULTS AND DISCUSSION

Laboratory tests were conducted to verify the proper functioning of the newly developed sensors. A series of tests were conducted using red clay to determine the amplitude of sensitivity of the sensor. Red clay, the finest material in suspension, is overwhelmingly present in the rivers of the Paraná River basin. Experimental batches of suspended sediment concentrations of 10, 20, 30, 40, 50, 70, 100, 150, and 200 mg/L were prepared to test the sensors. This range of concentrations was typically of concentrations in rivers of the region. Results from the laboratory tests showed an excellent correlation between SSC and the voltage output from the sensors (fig. 6). As the SSC became greater, the voltage response was lower. The sensors could be modified to shift or increase the range of amplitude in readings by adding appropriate additional resistors. For most of the conditions found in these rivers, this was not necessary; however, variable resistors were installed to increase the range of amplitude. Resistors were set for the sensors in some of the rivers to be able to read up to 500 mg/L of sediments.

From laboratory experiments it was observed that the equations that relate SSC to voltage from the turbidity sensor are either linear or follow the equation below:

$$y = b \times e^{a \cdot x} \tag{1}$$

where

- y = suspended sediment concentration (mg/L)
- x = output voltage of the turbidity sensor
- a, b = equation coefficients

A base curve for the sensors can be defined in the laboratory using the analyzed samples. The equation was solved using the format:

$$x = \frac{\ln(y/b)}{a} \tag{2}$$

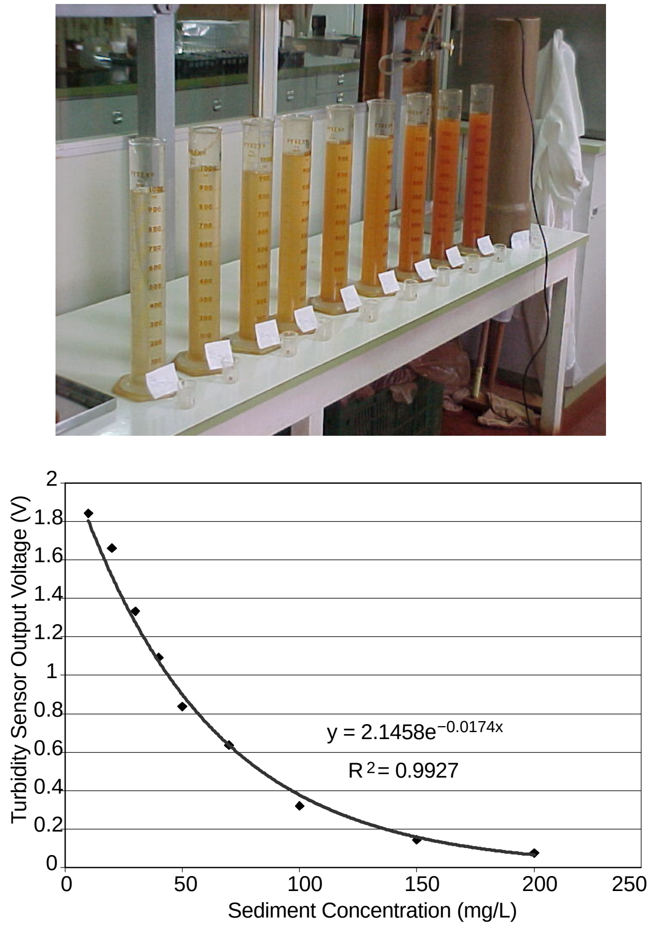

Figure 6. Samples used to test turbidity sensor.

This equation can then be used to adjust turbidity voltage output values between samples, which can be applied on a weekly or bi−weekly basis. A linear fit can also be used for low SSC in rivers with little observable deviation in accuracy; however, care should be taken when there is an observable rapid decrease in voltage output from the turbidity sensor, which indicates a peak in SSC. This peak in SSC is always accompanied with a rapid increase in flow rate. For this time period a more critical analysis is necessary. However, as mentioned earlier, during most of the year variations in SSC are gradual and linear calibrations provide adequate results. For small rivers changes in SSC were observed within a few hours; however, for the larger rivers significant changes in SSC were more gradual.

Ten monitoring stations with the newly developed turbidity sensors were installed in the southern Paraná River basin that delimits the Itaipu hydroelectric dam and the Porto Primavera and Rosana Dams in the state of São Paulo. Two sensors were installed at the entrance of the reservoir, one at the exit, two in rivers draining from each side of the reservoir, one below the other dams in the Paraná River, and the remainder in major rivers of the basin draining into the reservoir. The difference between the amount of sediment entering and leaving the reservoir is used to estimate the sedimentation rate of the reservoir.

Field testing and subsequent continuous use provided insight into the functionality of the sensors. Figure 7 shows a typical comparison between turbidity sensor output voltage and river stage height for a small river in the basin with an average flow rate of 8.5 m^3/s. A clear relationship is observed between peak stage heights and sensor output voltage. A low voltage output indicates a high SSC, which occurs as stage height peaks, but not necessarily at the same rates. Figure 8 shows the relationship observed between turbidity sensor output voltage and flow rate for a large river in the Paraná River basin.

Initially, temperature variations of the water were not deemed important because of the relatively mild climate of the region. Nevertheless, hourly results for some of the smaller rivers did show a fluctuation between day and night in some of the data either because of temperature changes or variation in sunlight intensity. The effect is more noticeable with clear and shallow flows for the small river (fig. 7) when the stage height is below 0.7 m. This is not a problem for larger rivers where water temperatures are virtually constant; however, temperature corrections should be considered in future sensor models. Twenty−four hour moving averages solved most of these issues and provided an accurate measurement of sediment loads from each river as shown both in figures 7 and 8. Errors by either debris or battery failures were easy to identify, as observed in figure 8 for the dates between 5 and 8 January. As was mentioned previously, errors of this nature can either be corrected by using a 24−h moving average or by verifying results with flow rates to obtain continuity of data. Suspended sediment concentrations were first calculated using the data obtained from the turbidity sensors and the analysis of the water samples. These results were then compared to river flow rates. In general it is expected that SSC will start to increase when water flow rates increase; however the relationship between these two is not constant and we may see lower SSC at the beginning of a flow rate increase. It is necessary to adjust the equation over time to compensate for possible accumulation of algae or dirt on the turbidity sensor lens, even when maintenance is done on a regular basis.

From the field experience it was determined that manual water sampling should be done three times a week and additional times when large flow events occur. This amount of sampling at each monitoring station was sufficient to constantly calibrate and verify the sensors. Greater numbers of samples from each site would compromise the quality of sample analyses in the laboratory since only one laboratory technician was available to carry out the analyses.

The placement of the structures and buoys was also determined to be very important for the monitoring of the sediment transport in the river. For the cases we have studied in the rivers draining the Paraná River basin, the best places to put the metallic structures are behind pillars of bridges where the maximum turbulent water flow occurs. Buoys should also be placed in the turbulent region behind the pillar of a bridge as shown in the picture in figure 5c; however, when there are no bridges, the buoys should be installed in the main flow stream of the river (fig. 5b). The turbulence helps to reduce the amount of sediment accumulating on the sensor lenses over time. It is also recommended that manual sediment sampling be done at the same location where the structure or buoys are placed.

Overall the structures and buoys functioned very well in protecting the turbidity sensors and allowing for accurate measurements. Sensors in buoys seem to function better for a longer period of time with little maintenance because the constant movement of the buoys limits the amount of debris or algae that can dirty the lenses of the probe. Nevertheless, it is recommended that maintenance be done at least once a month to clean the sensors and the buoys and to check that the sensors are working. Changing of batteries for data loggers, turbidity sensors, and water level meters should be done every 4 months. The downloading of the data from the data loggers, both for the turbidity sensors and the water level meters, should ideally be done at least every 2 months or

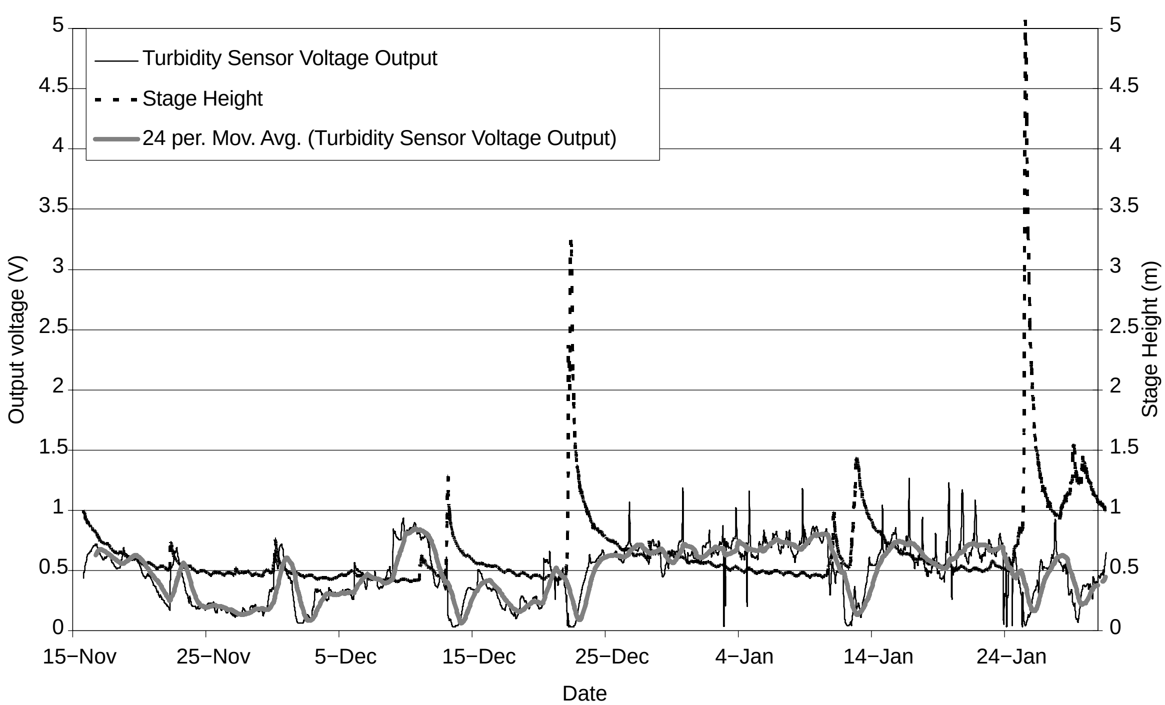

Figure 7. Turbidity sensor voltage output vs. stage height results for small river in Paraná River basin.

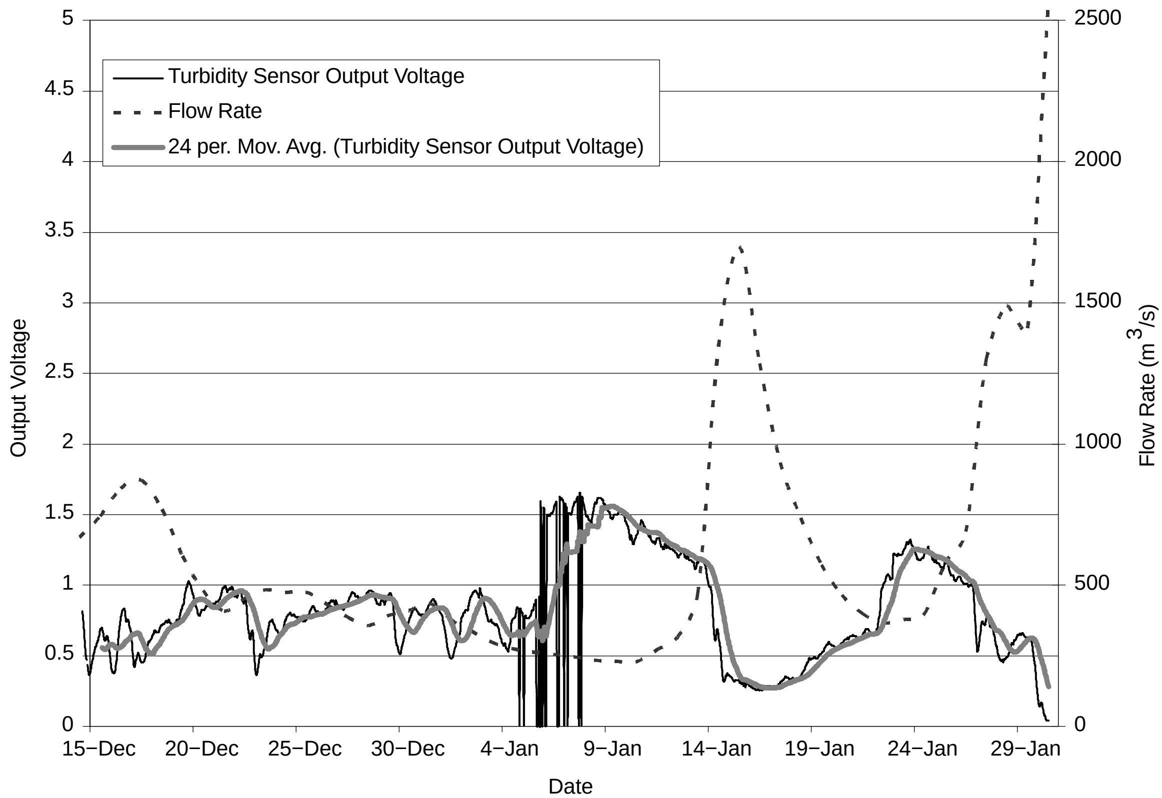

Figure 8. Turbidity sensor voltage output vs. flow rate results from large river in Paraná River basin.

every time the monthly maintenance is carried out. Even though loggers may hold greater than 6 months of data, downloading data in shorter intervals minimizes the event of any unforeseen loss of data. It is also recommended that in critical stations, such as the entrance to the reservoir, an additional turbidity sensor be installed as a back up.

After analyzing the results, it was observed that most of the sediment load in the rivers is transported by a few large events each year as shown in figures 9 and 10. This confirms Sun et al. (2001), who reported that large storms can transport the majority of the annual sediment load. Figure 9 shows daily sediment load results from the river that contributes the largest amount of sediment to the reservoir and figure 10 shows the monitoring results from the smallest river. Both these results indicate that most of the sediment load contributed by these rivers to the reservoir occurs in six or fewer major events annually. Thus, it is of extreme importance to continually monitor river sediment to accurately estimate sediment load contributions, otherwise major events may be missed which could lead to underestimating the amount of sediments being contributed to the reservoir.

Even though the monitoring system was shown to work well, additional improvements could be made by improving sensors, increasing frequency of sampling, and developing the capability for continuously measuring other parameters such as bed load and water quality. For rivers within the Paraná River basin, bed load has been estimated to be between 5% and 10% of total sediment load (internal studies at Itaipu reported by CONAM, 1978 – Consorcio para Estudos do Meio Ambiente and G.E.A., 1989 – Geologia e Engenharia Ambiental, Ltda.). The fraction of bed load was determined by direct measurements of bed load using sediment traps placed at the bottom of the river and compared to suspended sediment measurements taken at various depths of the river at the same location. Measurements of bed load and suspended sediment load at different river stages enabled an estimation of a bed load fraction for each river. Additional research, however, is needed to develop new equipment to constantly and accurately monitor bed load, particularly for the rivers containing larger amounts of sands. Additional water quality information for these rivers would also be the next sensible step in the monitoring. The buoys and structures could be used to house equipment to measure additional parameters such as pH, dissolved oxygen, conductivity and others.

Summary and Conclusions

The system developed to monitor sediment transport in rivers has proven to be effective for providing continuous sediment load results. The approach uses a combination of specifically developed turbidity sensors, water level meter, manual sediment sampling, and laboratory analyses. The turbidity sensors are used to estimate sediment concentrations at each specific site. The turbidity sensors work by detecting the clarity of the water using a 660−nm light beam from a LED and an optical sensor (OPT101). These sensors were custom built to minimize battery power consumption while taking readings at constant intervals and to withstand harsh river environments. Manual sediment samples taken on a regular basis three times a week are used to verify and continuously calibrate the turbidity sensors. Data from the water level meter and turbidity sensors allow computation of the water flow rates and suspended sediment loads for each of the rivers as well as the amounts of sediment load entering the reservoir.

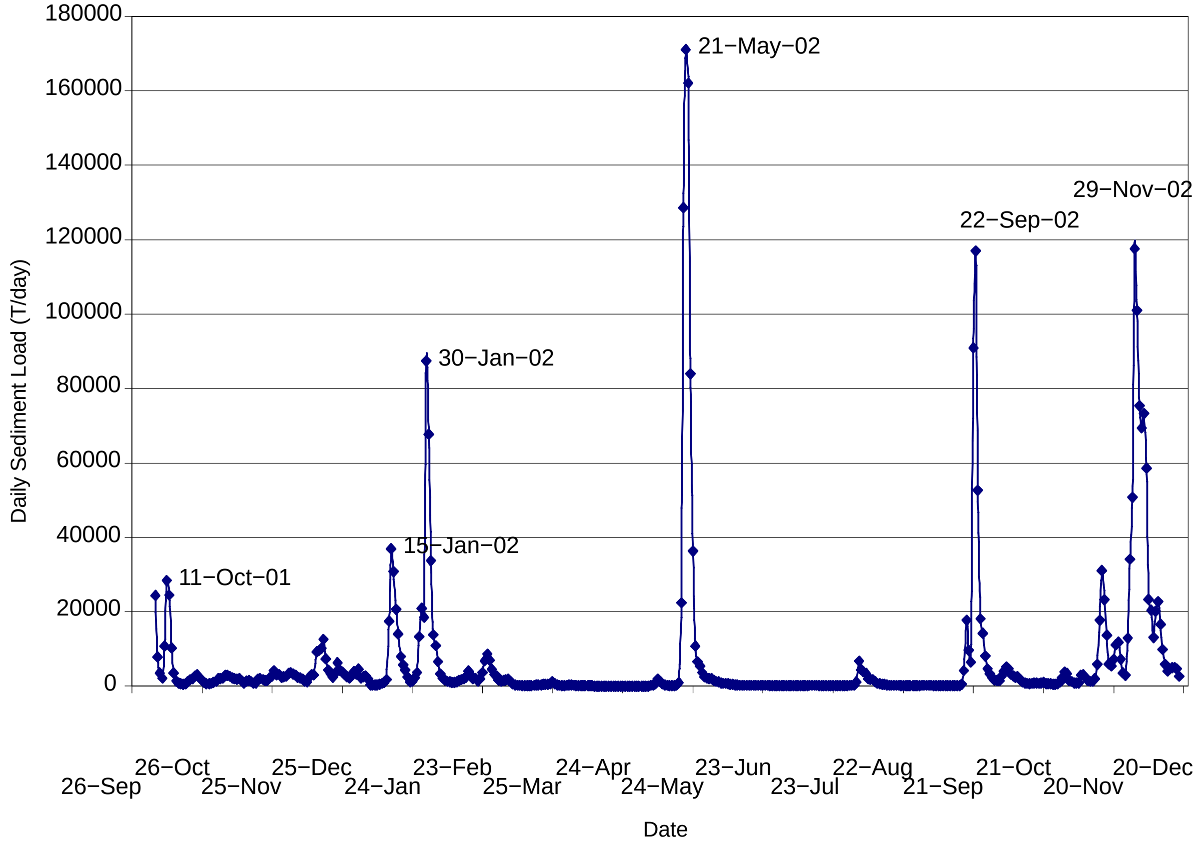

Figure 9. Daily sediment load for large river in the Paraná River basin.

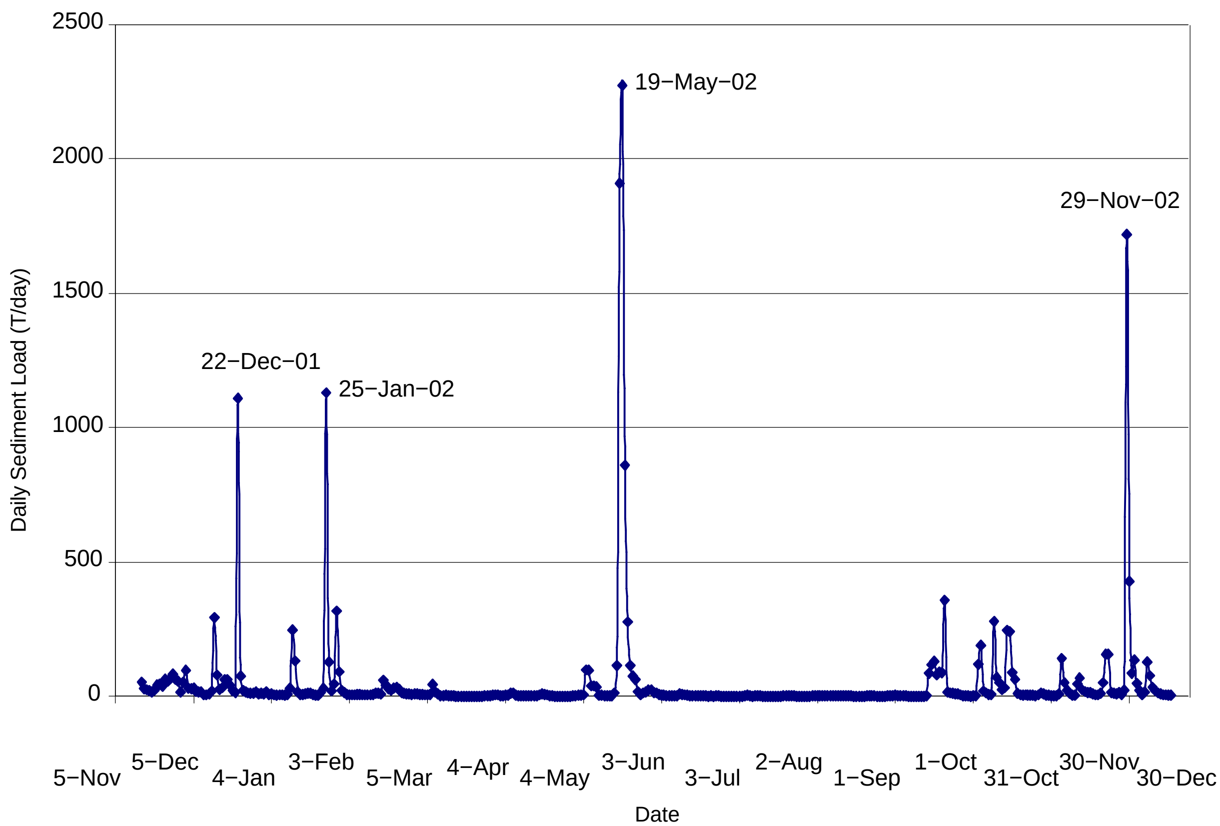

Figure 10. Daily sediment load for small river in the Paraná River basin.

The turbidity sensor output correlated well with laboratory determined sediment concentrations. Field results showed good correlations between manual sediment sampling, river stage height, and the sensor output. Two specific structures were designed to house the sensors: buoys and fixed structures. Each provided adequate protection for the equipment, thereby allowing monitoring under harsh river conditions. Optical sensors in buoys required less maintenance because the constant movement maintained the sensor lens free of algae and other debris for longer periods of time. Nevertheless, downloading of data and maintenance of structures and sensors should be done at least once a month.

Monitoring results showed most of the sediment load occurs in a few large flow events throughout the year and demonstrated the importance of a continuous monitoring system. Additional improvements to the system could be made by developing equipment to continuously monitor bed load and water quality.

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